Proceedings of the First Pacific Rim Thermal Engineering Conference, PRTEC
March 13-17, 2016, Hawaii's Big Island, USA

PRTEC-14487

A COMPARISON STUDY OF LAMINAR BURNING VELOCITY MEASUREMENT IN UNSTRETCHED FLAMES

Dong Chan Kim[1], Keun Seon Sim[1], Kee Man Lee[1*] and Dae Won Kim[2]

[1]Department of Mechanical and Aerospace Engineering, Sunchon National University,
413 Jungang-ro, Sunchon, Jeonnam, 540-742, Korea
[2]Department of Automotive Engineering, Jeonnam Provincial College,
152 Juknokwon-ro, Damyang-eup, Damyang-gun, Jeonnam, 517-802

ABSTRACT

This article describes a comparison investigation on the laminar burning velocities measurement methodology of simulated synthetic natural gas (SNG) flames. In this work, four ways were employed as an experimental measurement method. First method was an angle method of Bunsen flame, second was an adjusted area method using an adapted annular stepwise diverging tube. The third method was an unstretched flat flame by counter-flowing burner, and the final method by a bomb combustor was employed. These results were also compared with numerical calculation based on CHEMKIN package with GRI 3.0 and USC-II mechanism. As an experimental conditions, hydrogen content of SNG fuel was 3%, and the equivalence ratio was adjusted from 0.8 to 1.4. From results of this work, it was found that the laminar burning velocity of SNG fuel was the fastest result in equivalence ratio of 1.1, and the various measurement methods showed the similar trends. The employed ways were also evaluated each other

KEYWORDS: Laminar Burning Velocity, Bunsen Flame, Annular Diverging Channel Tube, Counter-flow Burner, Cylindrical Bomb Combustor,

1. INTRODUCTION

Natural gas demand and market prices have been risen continuously. The reserves of oil and natural gas are limited in decades. However, reserves of coal still have much than oil and natural gas. Thus, comprehensive study of synthetic natural gas (SNG) has been actively conducted. The SNG was gasified in high temperature and pressure. It is attracting much attention in recent because it is economical and good substitute for natural gas.

The main composition of SNG is methane, so it can substitute for natural gas. However, because it includes a few hydrogen (H_2), the combustion characteristics like flame speed and ignition could be altered, so that it is necessary to examine the validity of SNG fuel on the present facilities.

One of combustion's primary physical quality is a laminar burning velocity. It is principal parameter of combustion performance and base for turbulent burning velocity. It is also important element for optimization and design of combustion system.

Focus of this article is to find appropriate measurement method on laminar burning velocity in SNG fuel including hydrogen 3%. They are an angle method of Bunsen flame, adjustable area method using an annular stepwise diverging channel tube and unstretched flat flame method using a counter-flowing burner. Last methodology was measured by using spherical flames in cylindrical bomb chamber. Some of above methods have been extensively employed by many studies for measurements of laminar burning velocity. It has drawn the particular attention due to its simple flame configuration and well-known flame stretch rate. And then, these results were also compared with numerical calculation results. These computations were conducted by PREMIX code based on CHEMKIN package with GRI 3.0 and USC-II mechanism.

*Corresponding Author: kmlee@sunchon.ac.kr

2. EXPERIMENTAL SECTION

In present work, various methodologies were employed to compare the laminar burning velocity of SNG fuel. This section briefly explains on these experimental conditions and methods, apparatus.

2.1 Experimental Conditions

The experimental conditions are shown in Table 1. They consist of fuel kinds, oxidizer, equivalence ratio and composition ratio of simulated SNG fuel. Fuel and oxidizer were used with high purity methane, propane, hydrogen of 99.999%, and air of 99.99%, respectively.

Table 1 Experimental conditions.

Fuel	Simulated SNG fuel (CH_4, C_3H_8, H_2)
Oxidizer	High purity Air
Equivalence ratio (Φ)	0.8~1.4
Composition ratio of simulated SNG fuel (%)	$CH_4 : C_3H_8 : H_2$ = 91 : 6 : 3

2.2 Experimental Methodologies and Apparatus

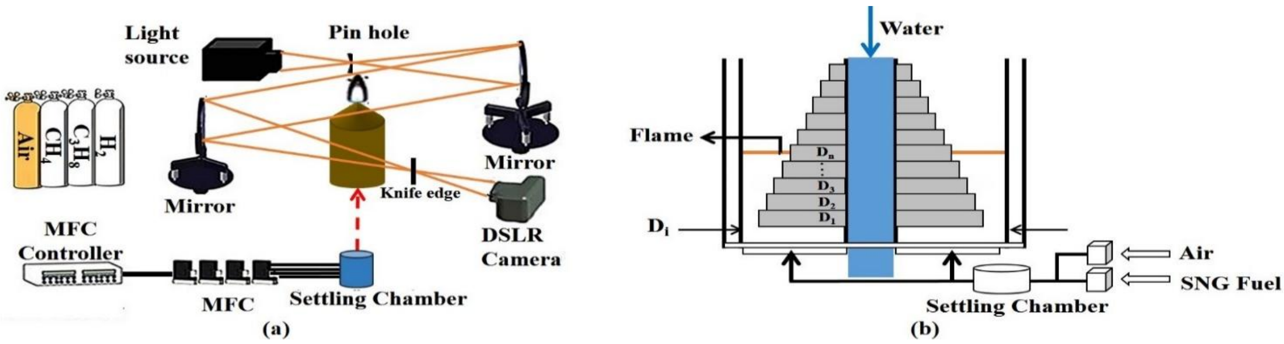


Fig. 1 Schematic diagram of (a) Schlieren system sand (b) annular stepwise diverging channel tube

Angle method. This method using Schlieren systems is shown in Fig. 1a. Nozzle flames have been studied extensively in this case, and most of laminar burning velocity data have been obtained by angle method.

$$S_u = U_0 \sin\theta \quad (1)$$

The laminar burning velocity can find in equation (1). For this method, the Bunsen flame is usually used to obtain it, which is calculated by multiplying the premixed mixture velocity (U_0**)** and the sine of the flame angle (θ). In this Bunsen burner technique, the flame stretch did not consider. Hence, flame stretch will be made to expect a slight increase in burning velocity.

ASDC method. The method using annular stepwise diverging channel (ASDC) tube and it is shown in Fig. 1b. The ASDC tube has been detailed previously [5]. The mixture gas flows into vertical tube, and then the burnt flame by ignition is located at n-step point. This flame location is considered as flame propagation velocity. Above explanation is shown in equation (2).

$$V_n = \frac{Q}{A_n} = \frac{4Q}{\pi(D_{in}^2 - D_n^2)} \quad (2)$$

Where Q is total rate of mixture gas and it is controlled with a constant flow rates of 10L/m, and D_{in} means diameter of the inner quartz. This methodology has advantage to confirm the burning velocity in real time.

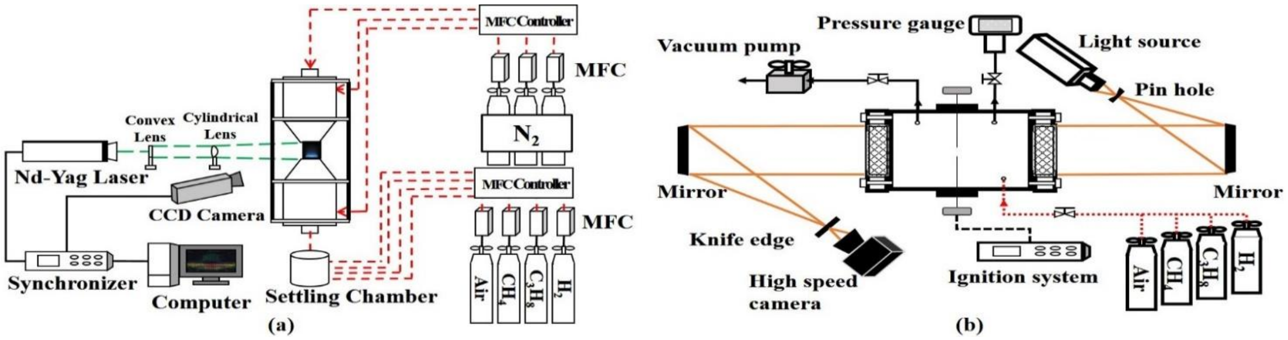


Fig. 2 Schematic diagram of (a) counter-flow burner with PIV systems and (b) cylindrical bomb chamber

Counter-flow method. The counter flow methodology of mixture gas and nitrogen impinged each other from two opposing burner nozzles is shown in Fig. 2a. Figure 2a also shows the PIV (Particle Image Velocimetry) system as a measuring instrument. A stagnation plane is generated between two burners. Unstretched burning velocity in this work can be determined by extrapolated stretch rate of zero point from measured results. Hence, the global stretch rate is explained by equation (3).

$$K = \frac{U_0}{L} \tag{3}$$

Where *K*, U_0 are stretch rate, unburnt mixture gas velocity, and *L* is distance of between two burners, respectively. The unburnt mixture velocity has a minimum value at just before reaction zone, which is defined as burning velocity.

Spherical flame method. Last methodology is employed using cylindrical bomb combustor and is shown in Figure 2b. This experimental apparatus is consisted of high speed camera and Schlieren systems. Gas mixture is ignited at the center point. The initial pressure = 0.1 MPa, fps=6000.

$$S_b = \frac{dr}{dt} \tag{4}$$

The burned velocity, S_b is calculated from the instantaneous flame radius measured from the experiments, it can be using equation (4). The total stretch rate applied to flame, *K* is defined as:

$$K = \frac{1}{A}\frac{dA}{dt} = \frac{1}{4\pi r^2}\frac{8\pi r dr}{dt} = \frac{2}{r}S_b \tag{5}$$

Where *A* is the flame surface area. There are linear relationship between the flame velocity and the total stretch rate. This is quantified by burned gas Markstein length, and is defined at equation (6).

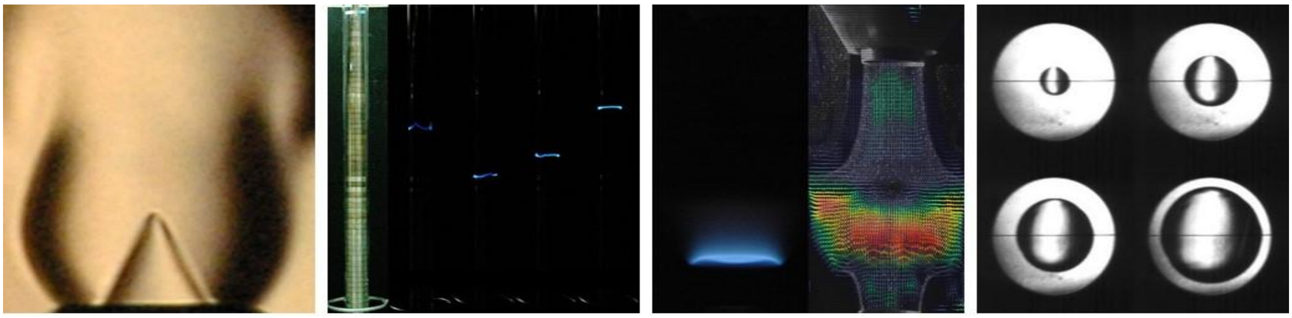
$$S_b = {S_b}^0 - L_b K \tag{6}$$

Where ${S_b}^0$ is unstretched flame speed, and is obtained as extrapolated value of S_b at *K*=0, Markstein length (L_b) is best straight line fit of experimental data. Above equation is applicable when flame is thin. Laminar burning velocity is calculated from one-dimensional flame velocity and density ratio using next equation (7).

$${S_u}^0 = {S_b}^0 (\frac{\rho_b}{\rho_u}) \tag{7}$$

Where ρ_b is the density of burned products and ρ_u is the density of the unburnt mixture, and this equation is assumed to be in equilibrium and is calculated.

Numerical calculation. The numerical calculations by PREMIX code were conducted to compare the results of experimental measurements. The GRI 3.0, that is well known as appropriate calculation for CH_4 flame, and USC-II mechanism, that is suitable for C1~C3 hydrocarbon fuels including H2, were employed in this work.



(a) (b) (c) (d)

Fig. 3 Flame shape: (a) Schlieren image in Bunsen burner (b) photograph in ASDC tube (c) direct image (left) and PIV image (right) in counter flow (d) Schlieren images in cylindrical bomb chamber

3. RESULTS AND DISCUSSION

3.1 Flame Shape

A Schlieren image of cone flame in Bunsen burner is shown in Figure 3(a). Next figure (b) shows flame direct photograph in ASDC tube measurement. It also shows that the flame positions according to equivalence ratio were adjusted at the corresponding to the n-step, which indicates the burning velocity directly. Most rapid burning velocity was located at lowest part of combustor. Figure (c) shows counter flow flame. The burning velocity was taken picture using the PIV systems with CCD camera. Right hand side in Fig. (C) shows the velocity profiles converted by ASCII file. Last figure (d) is Schlieren images captured in cylindrical bomb chamber.

3.2 Comparison of Burning Velocity

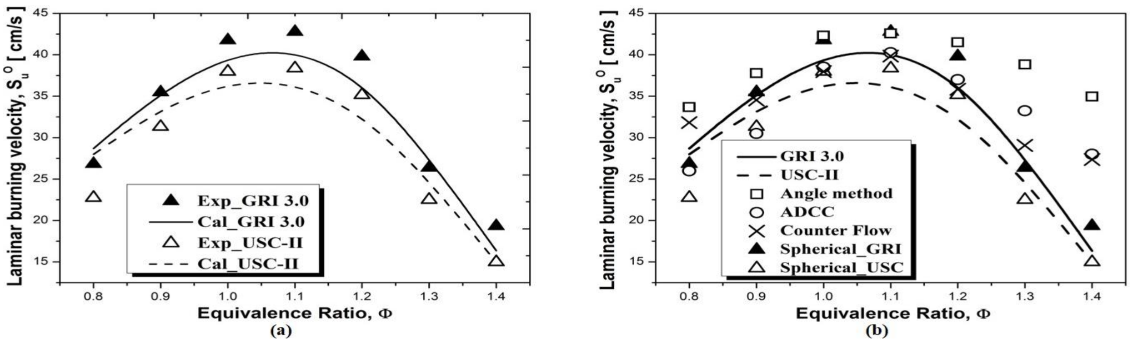


Fig. 4 (a) Laminar burning velocity by cylindrical bomb chamber and comparison with numerical calculations (b) Comparison of laminar burning velocity of four methods with numerical calculations

Figure 4(a) shows the experimental and numerical results of unstretched spherical velocity in SNG fuel with 3% hydrogen. As is shown in this figure, we can show that two different results in experimental expression were presented according to the employed calculation mechanism even if the experimental data had given as one result. Such different results were attributed to the different density data of burnt gases when the unstretched burning velocity was calculated from equation (7). That is, the reason is that the density properties were different from each other in applying of burnt gas density data between GRI 3.0 and USC-II.

Figure 4(b) shows that laminar burning velocity was measured by four methods using Bunsen burner, ADCC tube, counter flow burner and spherical bomb chamber, respectively. Solid line shows the results obtained from numerical calculation with using GRI 3.0 mechanism. And the dotted line is result of USC-II mechanism. For the equivalence ratio range examined (Φ=0.8-1.4), the burning velocity increases with increase of equivalence ratio till Φ=1.1 and starts declining with further increase in equivalence ratio. There are difference in burning velocities because of the characteristics of SNG fuel including a small hydrogen.

When it is compared to the respective methodology, angle method by Bunsen flame was simplest methodology in this work, but it was not good for considering stretch effect. ASDC tube method was relatively simple methodology, but it was also difficult to exclude the heat-up influence of quartz tube by flame heat. However, it had advantage to monitor propagating flames in real time, which is made to count the burning velocity easy. For the counter flow method, we could trust this result because stretch rate is zero. Counter flow method was measured by CCD camera that could trace the particle. However, the particle was difficult to be able to generate in between the close nozzles.

4. CONCLUSIONS

This study was carried out to compare the various experimental measurement methods on the laminar burning velocity in SNG fuel including 3% hydrogen. The Bunsen burner, ASDC tube, counter flow burner and bomb cylinder were employed in present work. The numerical calculations with GRI 3.0 and USC-II mechanism were also conducted to compare experimental measurement results. These results are as follows;

Angle method by Bunsen flame represented faster than other methods due to the stretch effect at top of cone flame. And, it was simplest methodology in this work. However, the Bunsen flame has some disadvantages. One of those is low accuracy, and only average burning velocity can be obtained. Moreover, it is not suitable for measuring the very fast flames. ASDC method would be relatively simply measurement and had advantage to measure burning velocity in real time. However, it needs a very careful skill because the fast reading of flame position must be accomplished before making hot of quartz tube by flame heat. Nevertheless, it was easy to monitor the propagating flames corresponding to burning velocities in the combustor tube. In present work, the counter flow method was best coincided with the numerical calculation except very rich condition of Φ=1.4, especially GRI 3.0 result. However, it needs complicated apparatus and laser diagnostics skills like PIV system. The cylindrical bomb method was comparatively coincided with the numerical calculations, especially USC-II result. However, it presents itself very sensitivity to the employed gases purity, that is, gas’s quality. And, it also has a difficult to supply fuel accurately.

ACKNOWLEDGMENT

This work was supported by the Energy Efficiency & Resources Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No.2015-2010-103050)

NOMENCLATURE

Φ	equivalence ratio		S_b	stretched burning velocity	(m/s)
V_n	n-step burning velocity	(m/s)	$S_b{}^0$	unstretched flame speed	(m/s)
K	stretch rate	(s^{-1})	L_b	Markstein length	

REFERENCES

[1] K.J. Kang, T.J. Park, K.M. Lee, “A Study on Combustion Characteristics of Synthetic Gas Air Lifted Premixed Flames with High Strain Rate in an Impinging Jet Combustion Field", The Korean Society of Combustion, Vol. 16, No.4, 2011, pp. 31-37

[2] B.G. Jeong, K.M. Lee, “Measurement of Laminar Flame Speed of Syngas (H2/CO) /Air Premixed Flame using the Bunsen Burner Method” The Korean Society of Combustion, No.44, 2012, pp. 181-183

[3] N. Bouvet, C. Chauveau, I. Gokaip, S.Y. Lee and R.J. Santoro, “Characterization of Syngas Laminar Flames using the Bunsen Burner Configuration", Int. Journal of Hydrogen Energy, Vol. 36, 2011, pp. 992-1005

[4] S.H. Yun, K.M. Lee, “A Study on the Laminar Burning Velocity Using an Angle Method and Annular Diverging Channel Combustor and Characteristics of Chemiluminescence" The Korean Society of Combustion, No.49, pp. 91-94

[5] Zhao Liu, M.J. Lee, N.I. Kim, “Direct Prediction of Laminar Burning Velocity Using an Adapted Annular Step-wise Diverging Tube" Proc. Combust. Inst. 34 (2013) 755-762

[6] J.H. Kang, B.J. Lee, S.H. Chung “An Experiment on the Concentration and Velocity Fields of Counter flow Premixed Flames" The Korean Society of Mechanical Engineers, Vol.17, No.11, 1993 pp. 2850-2856

[7] W.S. Song, T.M. Vu, J. Park, “Experimental Study on Flame Propagations and Cellular Instabilities in Biomass Derived Gas-Air Premixed Flames” The Korean Society of Combustion, No.42, 2011, pp. 33-42